CURRENT ISSUES IN HEAVY QUARK PRODUCTION

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We discuss heavy quark production in deep inelastic scattering (DIS).

Consider the effect of a charm quark (with mass m) being produced in neutral current DIS. For simplicity we concentrate on virtual photon exchange and neglect the bottom quark.

Precise data are now available on $F_2(x,Q^2)$. In pQCD the operator product expansion and asymptotic freedom allow one to calculate the scaling violations. This is incorporated in the factorization theorem where short distance effects are separated into coefficient functions and long distance effects into parton densities (for lowest twist terms), whose evolution is governed by the DGLAP equations. A mass factorization scale μ is thereby introduced. The corrections to such an analysis are of order Λ^2/Q^2. The coefficient and splitting functions have been calculated to order α_s^2 with massless quarks. The first problem is how the presence of a massive c quark affects the above analysis? In principle there should not be any problem because massless quarks were only used for calculational convenience. At small scales $\mu \ll m$ the three flavour splitting functions and parton densities should remain the same. The coefficient functions then contain terms in m. The c quark contribution in DIS $F_{2,\mathrm{c,EXACT}}(x,Q^2,m^2)$ can then be calculated in this fixed three-flavour number scheme with parton densities for u,d and s quarks (and antiquarks) and added to the light quark component $F_{2,\mathrm{LIGHT}}(x,Q^2)$ to form $F_2(x,Q^2)$.

As Q^2 increases large terms in $\ln(Q^2/m^2)$ develop which should be resummed to give stable predictions. This means that for $Q^2 \gg m^2$ the c quark becomes effectively massless and should be removed from the coefficient functions into the light parton densities. When this has been done there are four-flavour densities (including one for a c quark) and four-flavour massless coefficient functions. $F_{2,\mathrm{ZM-VFNS}}(x,Q^2)$ is the zero-mass variable flavour number scheme representation for DIS. Since the evolution in the DGLAP equations covers all scales there should also be a variable flavour number scheme (VFNS) which interpolates between the two descriptions above. Clearly the schemes are complementary in that there are overlap regions where one scheme is as good as another and maybe much simpler to use, but one has to be explicit in the construction of a VFNS by specifying which parton densities and which coefficient functions are used. The ACOT scheme is an order α_s VFNS and recently a simplified version of it has been proposed [1]. The CTEQ5 parton density set [2] contains both fixed flavour densities and VFNS sets which use the ACOT scheme.

What is known in higher order pQCD? In [3] we established an all-order relation between $F_{2,\mathrm{ZM-VFNS}}$ and $F_{2,c,\mathrm{EXACT}}$ which implied an all-order relation between light and heavy quark densities. The operator matrix elements containing the terms in powers of $\ln(\mu^2/m^2)$, which should be incorporated into boundary conditions on the evolution of the four-flavour densities (including a c quark density), were calculated to order α_s^2. Starting from a three-flavour set of densities in [4] we have constructed a set of four-flavour densities in [5] which satisfy these boundary conditions and resum the large logarithms. Each set has a different gluon density and satisfies the momentum sum rule. Thorne and Roberts [6] tried to construct coefficient functions for use with such ZM-VFNS parton densities but concluded that the scheme was too complicated. They then proposed a different scheme based on continuity of $dF_2(x,Q^2)/d\ln(Q^2)$ across flavour thresholds. This TR scheme has been implemented in order α_s in the MRST98 [7] (and subsequent MRST) parton density sets.

Two VFNS's now exist in order α_s^2. One is called the CSN scheme [8]. It uses heavy quark coefficient functions and begins with a term in order α_s^0. The second is called the BMSN scheme [8 9] and is based on massless coefficient functions. The differences between all the VFNS's can be attributed to three ingredients entering their construction. The first one is the mass factorization procedure carried out before the large logarithms can be resummed. The second one is the matching condition imposed on the c-quark density, which has to vanish in the threshold region of the production process. The third one is the construction of both three-flavour and four-flavour sets of parton densities, respecting the relations in [3]. Although designed to calculate $F_2(x,Q^2)$ both the BMSN and CSN schemes divide it into two pieces called $F_{2,c}(x,Q^2,\Delta)$ and $F_{2,\mathrm{LIGHT}}(x,Q^2,\Delta)$ respectively. The quantity Δ separates the collinear $c-\bar{c}$ pair production from the noncollinear pair production and is the value of the invariant mass above which they can be detected. This split makes $F_{2,c}(x,Q^2,\Delta)$ collinear safe. The BMSN and CSN schemes are designed so they yield the same result as the three-flavour NLO expression for $F_{2,c}(x,Q^2,\Delta)$ at $Q^2=m^2$. In this region the four-flavour scheme fails. As Q^2 increases there are differences between the BMSN, CSN and three-flavour schemes reflecting both how the higher order terms are resummed into densities and the influence of terms in m^2/Q^2. At large Q^2 both the BMSN and CSN results for $F_{2,c}(x,Q^2,\Delta)$ agree numerically with the four-flavour results. For $x\approx 10^{-3}$ and $Q^2=10^3$ $(\mathrm{GeV/c})^2$ both disagree by approximately ten percent with the three-flavour result showing that the resummation of the large logarithms is not a dramatic effect once one gets to order α_s^2. The differences increase at larger x which, for fixed Q^2, is closer to the threshold at $Q^2(x^{-1}-1) = 4m^2$ because effects due to terms in m are enhanced.

Note that we have designed the soft/collinear split above without introducing a fragmentation function. We can do this for suitably defined inclusive quantities. The next problem is the calculation of the single particle inclusive rate for producing D^* ($\bar{D}^*$) mesons. Every experimental measurement must specify thresholds (or regions in phase space) below which the mesons cannot be detected. Under these circumstances potential collinear divergences remain in the final state. Is it better to keep the c-quark massive to avoid them or to take the c-quark massless and absorb the singularities into fragmentation functions (and resum them via evolution)? Either way we need additional information on the parametrization of the fragmentation functions describing the transition from quarks to mesons. Also there is another scale p_t and a new set of logarithms. Which logarithms are more important? There is no gain in resumming terms in $\ln(Q^2/m^2)$ into either the parton densities or the fragmentation functions if they are not dominant. Does one need a VFNS for single particle inclusive production or only a fixed flavour scheme and where do they provide a better description of the data?

To begin we assume the differential production rate is measured at small Q^2 and is modelled by extrinsic production. The NLO exclusive program HVQDIS [10] uses three-flavour parton densities in the initial state and a massive c-quark to predict the rate. The reason for this is that potential collinear singularities involving the final state c-quarks are now controlled by m. We assumed a simple Peterson et al., type fragmentation function to model the transition from the $c(\bar{c})$-quark to the D^* ($\bar{D}^*$) meson. The final parameters are the pole mass m, the fragmentation parameter ϵ, the scale μ, which appears in the running coupling (and the parton densities) and the probability for $c \to D^*$. The differential rates for the D^* ($\bar{D}^*$) mesons measured in the H1 [11] and ZEUS [12] experiments are in good agreement with this NLO calculation. A recent comparison is available in [13]. The experimental groups have used HVQDIS to integrate over all phase space to produce a quantity called $F_{2,c\bar{c}}(x,Q^2)$, the charm component of $F_2(x,Q^2)$. However note this is based on the HVQDIS program, which does not include diffractive production, intrinsic charm or resummation effects at large and/or small x. It is also not the same quantity we defined above with the parameter Δ. Authors who claim agreement between their theory and this experimental result should be aware of this fact. HVQDIS has been used to produce distributions in the invariant mass of the $c-\bar{c}$ (or $D^*-\bar{D}^*$) pair and experimental results should be available soon.

The NLO calculation is complicated. Can one fit the same differential distributions and/or the experimental $F_{2,c\bar{c}}(x,Q^2)$ in a four-flavour scheme with a massless c-quark? This can be tried at two levels. First can one calculate the single particle inclusive distributions with massless quarks? Most of the D^* ($\bar{D}^*$) data is at small p_t so the only large scale is Q^2 (and μ^2). Therefore one needs to understand how to partition the potentially large terms in $\ln(Q^2/\mu^2)$ and $\ln(\mu^2/m^2)$ between the parton densities and fragmentation functions leaving a collinear safe partonic differential coefficient function. Then how about $F_{2,c\bar{c}}(x,Q^2)$? Can one integrate over the final states to remove the fragmentation function and give a four-flavour description at the level of the coefficient functions? The latter investigation is more involved because every time we integrate over a variable we encounter a potential new collinear singularity as $m \to 0$. These questions remain to be investigated.

We end with the comment that the all-orders proof of factorization in DIS including heavy quark effects given by Collins [14] contains a unitarity sum over *all* the final states and he therefore never defines a collinear safe charm contribution. Also the advantage of using massless coefficient functions in VFNS's was first proposed in [9].

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